

BIM-IoT integration for remote real-time concrete compressive strength monitoring

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ABSTRACT

Traditionally concrete strength determination has been a costly and time-consuming process, relying on periodic laboratory testing using compression tests on concrete-filled cylinders. To address these challenges, an innovative framework has been developed using the Internet of Things (IoT) technology-based low-cost wireless sensors. These sensors have been programmed to integrate with a real-time data monitoring platform using the Firebase cloud computing application. This framework allows remote real-time concrete compressive strength monitoring while reducing the need for on-site laboratory testing. This aspect can ultimately add digital competencies to the construction industry. The IoT-based data is further integrated with the Building Information Modeling (BIM) model of the structure, developing its Digital Twin (DT), which enables the concerned authorities to remotely access the concrete compressive strength parameters, particularly in the early stages. The proposed system presents notable advantages compared to traditional methods by enabling remote real-time monitoring of concrete strength parameters in the BIM environment and facilitating informed decision-making to optimize the construction schedule utilizing the Active BIM system. It serves as a pioneering advancement in internet/remote applications designed to monitor early-age compressive strength. By assisting project managers in timely actions such as formwork removal, post-tensioning, curing termination, and reshores removal, it generates significant cost savings in terms of labor and expedites the completion of construction activities.

1. Introduction

In the construction industry, concrete is a fundamental material that is used for building many different structures, including buildings, bridges, dams, and roads [1]. Concrete's compressive strength is an essential property that defines its structural integrity and durability, and therefore it is important to monitor the concrete strength throughout the construction lifecycle [2]. Notably, early-age concrete compressive strength holds particular significance in construction scheduling [3]. It allows project managers to accurately plan and sequence activities, ensuring efficient progress and timely completion. Concrete strength monitoring also helps in determining the appropriate time for opening

traffic on concrete pavement, and formwork removal, allowing for the smooth transition to subsequent construction phases [4].

To monitor early-age concrete compressive strength, standard destructive procedures like compressive strength tests of the standard cylinder ASTM C 31/C 31M are widely utilized [5]. While these tests ensure quality control and compliance with contractual requirements, they are not suitable for estimating in-place concrete strength due to factors like placement, compaction, and curing variations [6]. Additionally, standard-cured cylinders typically undergo testing after 28 days, making it challenging to determine early-age strength crucial for many activities like formwork removal or post-tensioning [7]. Hence, alternative approaches like nondestructive testing (NDT) of concrete

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gain significance. Unlike destructive tests on molded specimens, nondestructive in-situ tests are conducted directly on the actual concrete, aiming to estimate real-time compressive strength [8]. These tests measure properties correlated with compressive strength, requiring a pre-established relationship for estimation. However, they come with limitations, including time consumption, skilled personnel requirements, and the need for frequent testing [9].

The traditional approach of periodic testing for concrete strength evaluation no longer meets the demands of the modern construction industry [10]. Integrating IoT-based technologies into construction practices has shown significant progress in optimizing various aspects of projects, including enhancing multi-project material delivery processes [11,12]. However, there exists a gap concerning the effective integration of IoT and BIM methodologies. Active BIM, an emerging approach that emphasizes the concept of two-way data enrichment, holds the potential to address this gap. Monitoring concrete strength in real-time is crucial for ensuring quality and safety in construction projects [13]. While several studies have developed real-time concrete strength monitoring systems, their integration with BIM remains insufficiently discussed. Leveraging BIM tools is pivotal for fully utilizing this data and facilitating effective decision-making [14].

By integrating real-time data into BIM, stakeholders can access the concrete strength characteristics of a physical structure through a DT, which is a virtual representation of the said structure [15]. This DT provides a dynamic and interactive representation of the construction project, allowing stakeholders to assess progress, monitor concrete strength, and make informed decisions throughout the construction process [16]. The need for real-time concrete strength monitoring (RTCSM) and visualization in BIM and DT, arises from the industry's demand for enhanced efficiency, quality control, and proactive risk management. It empowers construction professionals to promptly identify potential issues, optimize construction workflows, and ensure that concrete structures meet the desired strength requirements, ultimately leading to safer and more durable built environments. The purpose of this research paper is to investigate the integration of IoT technology for real-time concrete strength monitoring and the use of BIM tools to visualize and analyze the collected data, presenting a comprehensive approach to improve construction quality, efficiency, and project outcomes.

The rest of the paper is structured as follows. Section 2 presents a review of the pertinent literature and discusses relevant studies on the principle of maturity and IoT-based devices in the construction industry along with BIM integration. It sets the foundation for the proposed framework's novelty which is addressed in Section 3. Section 4 details the developed approach, including the development of a low-cost maturity sensor, monitoring dashboard, and the framework of IoT-BIM integration. Section 5 presents the setup and results of the case study, demonstrating the accuracy and efficiency of the proposed system. The detailed process of BIM Integration has been discussed in section 6. Pertinent discussions and limitations of the study are presented in Section 7. Finally, Section 8 concludes the study.

2. Literature review

The strength of concrete is influenced by the hydration process of Portland cement, which is affected by factors like curing temperature and duration, materials used, cement type, water-cement ratio, and other parameters [17]. Maturity, as proposed by Saul, is based on time and temperature data collected during curing [18]. The concept of maturity in concrete suggests that concrete with the same mix, exposed to equivalent temperature–time conditions, will possess approximately equal strength, regardless of the specific combination of temperature and time that contributes to its maturity. This means that there is a unique relationship between hardness and aging ability for any combination of time and temperature this was termed as the rule of maturity [19]. The American Society for Testing and Materials (ASTM) officially

recognized this method as a standard in 1987. To comply with ASTM specifications, continuous monitoring of concrete temperature is necessary after pouring. Additionally, two alternative methods have been proposed to determine the maturity function, namely the equivalent age and the temperature–time factor [20].

The maturity properties of concrete are derived from the time–temperature curing process, utilizing the Maturity index, as shown in Fig. 1. Several researchers have explored the application of the maturity method, and as a result, a variety of maturity functions have been proposed [21,22]. Many of these functions have been accepted in widely recognized standards and guidelines [23,24]. Saul equation is most widely adopted due to its simplicity and easiness.

$$M(t, T) = \sum_{k=0}^t (T - T_0) \cdot \Delta t \quad (1)$$

The maturity index of concrete ($^{\circ}\text{C h}$) is represented by the function $M(t, T)$, T is the measured temperature ($^{\circ}\text{C}$) at Δt interval (h) and T_0 represents the datum temperature of concrete's mix design ($^{\circ}\text{C}$). Eq. (1) denotes the maturity function of concrete. The term datum temperature pertains to the temperature of concrete where there is no further increase in its strength gain increase.

To determine the strength of concrete based on its maturity index, a strength-maturity relationship is established. This equation is typically derived by calibrating the crushing strength with the maturity index for mix design using regression curves generated through machine learning (ML) techniques [25]. To establish a relationship between concrete strength and maturity, Plowman developed a method based on the assumption that the temperature's initial rate of strength gain follows a linear function [26].

$$S = a + b \log(M) \quad (2)$$

where S represents the concrete strength in compression. The constants “ a ” and “ b ” are coefficients that are specific to the concrete mix and are determined through experimental calibration and M is the maturity. The compressive strength demonstrated a linear correlation with the constants a and b . Eq. (2) gained popularity due to its simplicity, resulting in a straight line when the maturity index axis is represented on a logarithmic scale. However, this equation has its limitations. It does not accurately depict the relationship between strength and maturity index when the maturity index is either low or high. Thus, a more accurate linear hyperbolic equation has been explained by Cario and Knudsen [27].

$$S = S_u \frac{k(t - t_0)}{1 + k(t - t_0)} \quad (3)$$

where S is the compressive strength of concrete at age t , S_u is the limiting strength, K is the rate constant equal to 1/day, and so is the age at the

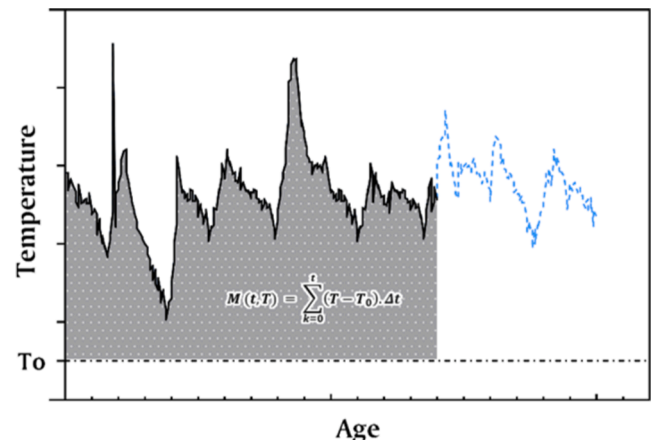


Fig. 1. Maturity function of the concrete.

start of the strength development. The advantage of the Cario-Knudsen equation lies in its ability to capture the non-linear behavior of concrete strength development. It recognizes that the relationship between strength and maturity index may not be strictly linear and adjusts the curve accordingly. This equation has been widely used in research and engineering practice to improve predictions of concrete strength based on various parameters, allowing for better quality control and optimization of concrete mixtures and curing processes.

The use of the maturity method presents numerous benefits over the traditional quality control methods utilized for verifying strength [28]. Not only does it provide a more precise reflection of the actual concrete strength gain in place, but it also enables the measurement of strength at any desired time and frequency until the required strength level is achieved. This adaptable approach leads to enhanced scheduling and timing of strength-reliant construction tasks, such as backfilling, opening concrete pavement traffic, post-tensioning, and formwork removal.

In recent years, significant advancements have been made in the architecture of IoT systems, with fog and cloud computing playing major roles in enhancing efficiency [29]. Fog computing brings cloud services closer to where data is generated, reducing delays. Cloud computing stores and analyzes the vast amounts of data IoT devices produce, helping industries like healthcare and manufacturing [30]. Combining fog and cloud computing makes IoT systems stronger and smarter, benefiting businesses and people's lives.

The construction industry similar to others has also witnessed significant advancements in technology, particularly with the advent of the IoTs and BIM technologies [31,32]. Multiple studies have proposed innovative frameworks that leverage the integration between BIM and the IoT to address challenges in different construction projects. Ding *et al.* [33] introduced the concept of smart steel bridge construction, aiming to tackle the issues of uncontrollability and inefficiency in traditional steel bridge projects through the integration of BIM and IoT technologies. Similarly, Too Han *et al.* [34] presented a BIM-IoT and IC-integrated framework for advanced compaction quality monitoring and management, utilizing BIM's high-fidelity virtual assets for data integration and visualization. Moreover, Qain *et al.* [35] designed a tunnel automatic monitoring system based on BIM and IoT, employing various sensing devices inside the tunnel and satellite data to collect monitoring data. These studies collectively demonstrate the potential of BIM and IoT in transforming construction practices, providing fundamental platforms for efficient data management, visualization, and monitoring across different infrastructure projects.

There are several studies aimed at determining concrete strength through real-time monitoring, yet they often encounter implementation challenges due to the costly nature of the sensing devices utilized. For example, Mojtaba *et al.* [36] developed a BIM-based system for monitoring structural health in modular buildings, focusing on vibration, strain, and deformation during transit and installation. Their framework integrates automated sensor data acquisition and visualization into the BIM model to enhance preinstallation monitoring. Karthik *et al.* [37] explored the integration of digital BIM and IoT for real-time monitoring and decision-making on structural integrity, connecting virtual sensors to IoT data for responsive visualization. Meanwhile, Micheal *et al.* [38] emphasized the necessity of SHM in civil engineering, proposing the IoTs integration to automate monitoring and processing. Their methodology, validated experimentally, introduces a DT for real-time data presentation, promising advancements in SHM practices.

In this study, the Active BIM approach is adopted rather than traditional IoT-based methods. While previous research has focused on developing IoT-enabled systems just for monitoring concrete properties, such as strength and shrinkage, during early construction phases [39], the present study aims to enhance this approach by integrating such systems in the BIM environment [40]. Various methods for determining concrete strength are discussed, some are recognized by ASTM and relevant standards, while others are not. The innovative aspect lies in integrating data collected by such a system with a BIM model. Although

a few studies connect IoT-based Structural Health Monitoring (SHM) devices with BIM models, there's little literature available that utilizes the ASTM standard method of Maturity for determining concrete strength and then integrates it with the BIM model.

The objectives of this study include achieving high-quality construction, precise performance and cost estimates, and continuous monitoring and control of the construction project. Additionally, maintaining an up-to-date information source within the BIM environment facilitates project stakeholders in obtaining a clear overview of the project for use in informed decision-making [41,42]. The integration of the maturity method with IoT brings us closer to the field of BIM and DT where the strength from the concrete member is visualized in nearly real-time. The effective utilization of the maturity method can lead to substantial cost savings due to improved timing and reduced reliance on a large number of specimens. This progress in construction practices not only enhances efficiency but also contributes to improved project outcomes.

3. Research gap

The conventional compression test used to determine concrete compressive strength lacks consideration for the various factors influencing concrete curing on construction sites, while also being costly and time-consuming [43]. Consequently, efforts have been undertaken to employ in-place testing techniques for assessing the actual rate of strength development [44]. Although studies have investigated utilizing IoT-based devices for concrete strength monitoring, there remains a gap in integrating this data with BIM tools. This research addresses this gap by employing the Active BIM approach to establish connections between DT concepts and IoT-based real-time monitoring applications. Specifically, the study targets three research gaps: implementing IoT-based cost-effective real-time concrete strength monitoring with a window-based user dashboard, developing ML-based regression models to establish strength maturity relationships according to ASTM standards, and integrating IoT technology with BIM tools to create a DT of the construction project.

This paper aims to address the specific gaps mentioned above by proposing an integrated real-time IoT-based smart system supported by machine learning (regression) and a window-based application. The system also connects to the Navisworks a BIM tool. The research objectives that this paper aims to achieve are threefold:

- To develop an IoT-based smart system supported by an economical temperature sensor with significant accuracy that would measure concrete temperature in real-time.
- A monitoring dashboard with ML-based regression functionalities to establish relationships between maturity and concrete strength as per the ASTM standards.
- Integration between the data collected through IoT devices and BIM tools to create a DT.

4. Framework and research methodology

In this section, the conceptual framework and methodology utilized in this study have been presented. An overview of the systematically organized stages of our research, along with the implementation details of the proposed system has been provided. Additionally, we outline the various structural components of the proposed system and how they are integrated to achieve the research objective.

4.1. Framework

In general, real-time concrete strength monitoring systems consist of a temperature and humidity sensor. The study followed existing studies on the development of IoT-based maturity as reported by Kampli *et al.* [45]. These sensors are responsible for recording the temperature

history of the concrete, in addition to ambient temperature and humidity levels. Fig. 2a. presents an overview of the block diagram illustrating the smart system for monitoring concrete strength. The central component of the system is the core controller, which serves as its primary control unit. The sensors are connected to this core controller, enabling it to manage their operation, collect data, and transmit the obtained values to a cloud database using wireless modules [46,47]. Devices used for measuring concrete strength employing the maturity approach are becoming more advanced as IoT technology evolves with time, with features like lower power consumption and easier operation. Fig. 2b illustrates the operational flowchart of a real-time system designed for monitoring concrete strength.

4.2. Methodology

In this research article, a novel framework for monitoring concrete strength in real-time using IoT technology is introduced. The proposed framework consists of four main tiers, namely the sensing layer, network layer, server layer, and application layer, as illustrated in Fig. 3. The sensing layer serves as the fundamental component of the framework, responsible for capturing data related to the concrete core temperature, ambient temperature, and humidity. These sensory inputs provide crucial information for estimating concrete strength. The network layer plays a vital role in data transmission and acts as a connector between different layers within the framework. It encompasses both wired and wireless networks to ensure seamless communication and efficient data transfer [48]. The server layer of the framework is responsible for processing data and storing it in the server database. On the other hand, the application layer serves as the central component that analyzes temperature data and employs various ASTM standard methods to calculate the concrete strength. Additionally, the window-based monitoring dashboard is equipped with the capability to locally store data in an xlsx file. This stored data is then synchronized with Navisworks, a BIM tool, to generate a DT of the construction site [49].

This study uses sensors wired to the ESP32 board, powered by an external source. The ESP32 (sensing layer), equipped with onboard Wi-Fi, connects to the internet (network) via a local wireless network. While a Wi-Fi router is utilized in this study, certain ESP boards feature an inbuilt GSM module for internet connectivity through GSM networks. The ESP32 records concrete temperature at specified intervals, storing it temporarily in its memory. Subsequently, it synchronizes with a time server to acquire timestamps for the data. Upon recording timestamps in

the ESP32 memory, authentication with the Google Firebase database is initiated. The stored temperature data, along with timestamps, is then transmitted to the Google Firebase database via the HTTP POST method (server layer).

In the database, data is structured in JSON format, where timestamps serve as keys and temperature data as values. Loading data into the BIM application is facilitated by a developed Windows application. This application retrieves sensor-specific data from the database, calculates concrete strength, and exports the results to a local file on the PC. When the BIM application Navisworks is opened, it loads the local file, displaying strength parameters for each structural component (Application Layer). Automation for new data involves reloading from the server as new data is stored, generating a new local file on the PC. With the use of Dynamo, Navisworks refreshes the strength parameters of each structural component from the updated local file.

4.3. Concrete strength monitoring using IoT technology

4.3.1. Hardware scheme

The IoT-based framework for monitoring concrete strength utilizes specific hardware components, including a Negative Temperature Coefficient (NTC) 10K thermistor, a DHT22 temperature and humidity module, and an ESP32 WROOM board. A depiction of these components can be seen in Fig. 4 and further details about the sensors and microcontroller board are available in Table 1. The ESP32 microprocessor is a prototype board developed by Espressif Systems. The board was chosen for this study because it is a powerful and versatile microcontroller module with built-in Wi-Fi and Bluetooth capabilities, ideal for IoT projects. It offers dual-core processing, extensive connectivity options, and ample memory for a wide range of applications, from home automation to wearable devices. Its affordability and community support make it a popular choice among developers. Furthermore, the board is available in a very small size which makes it ideal for locations where the sensor is supposed to be embedded in the concrete. For temperature sensing the study adopted the DHT22 sensor which is readily available to be used with Arduino and ESP boards due to its built-in libraries and humidity data measurement. The humidity data was included in the framework so that in the future advanced model for determining the maturity method could be adopted. However, DHT22 could be expensive especially if the sensor can't be retrieved from the concrete so the experiments were carried out on NTC thermistors. The study aimed to use hardware that is relatively affordable and easily available in

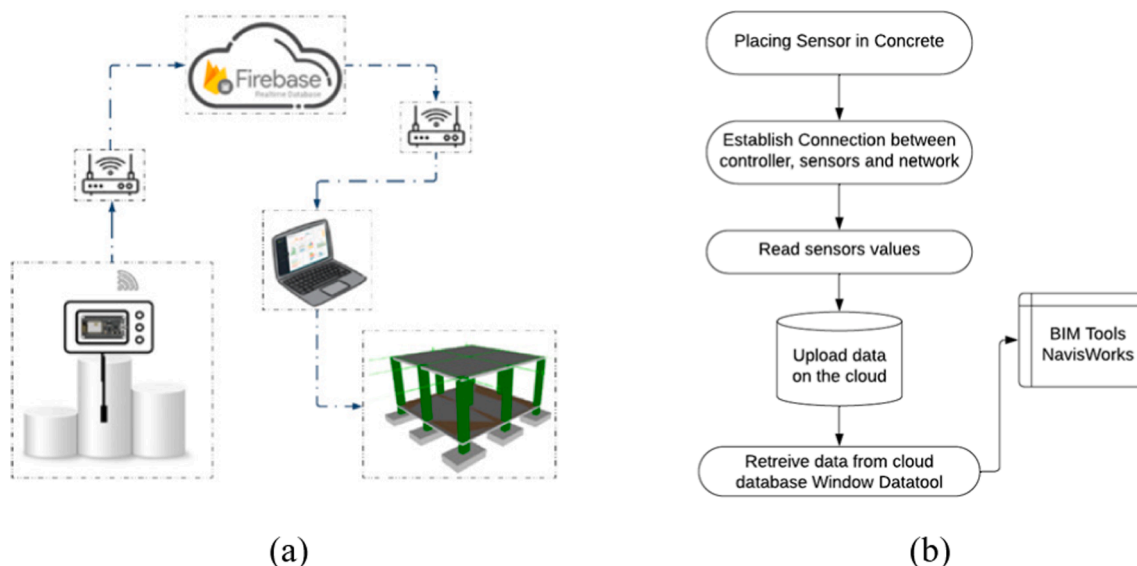


Fig. 2. (a) Taxonomy diagram of real-time concrete strength monitoring system (b) Working of real-time concrete strength monitoring system.

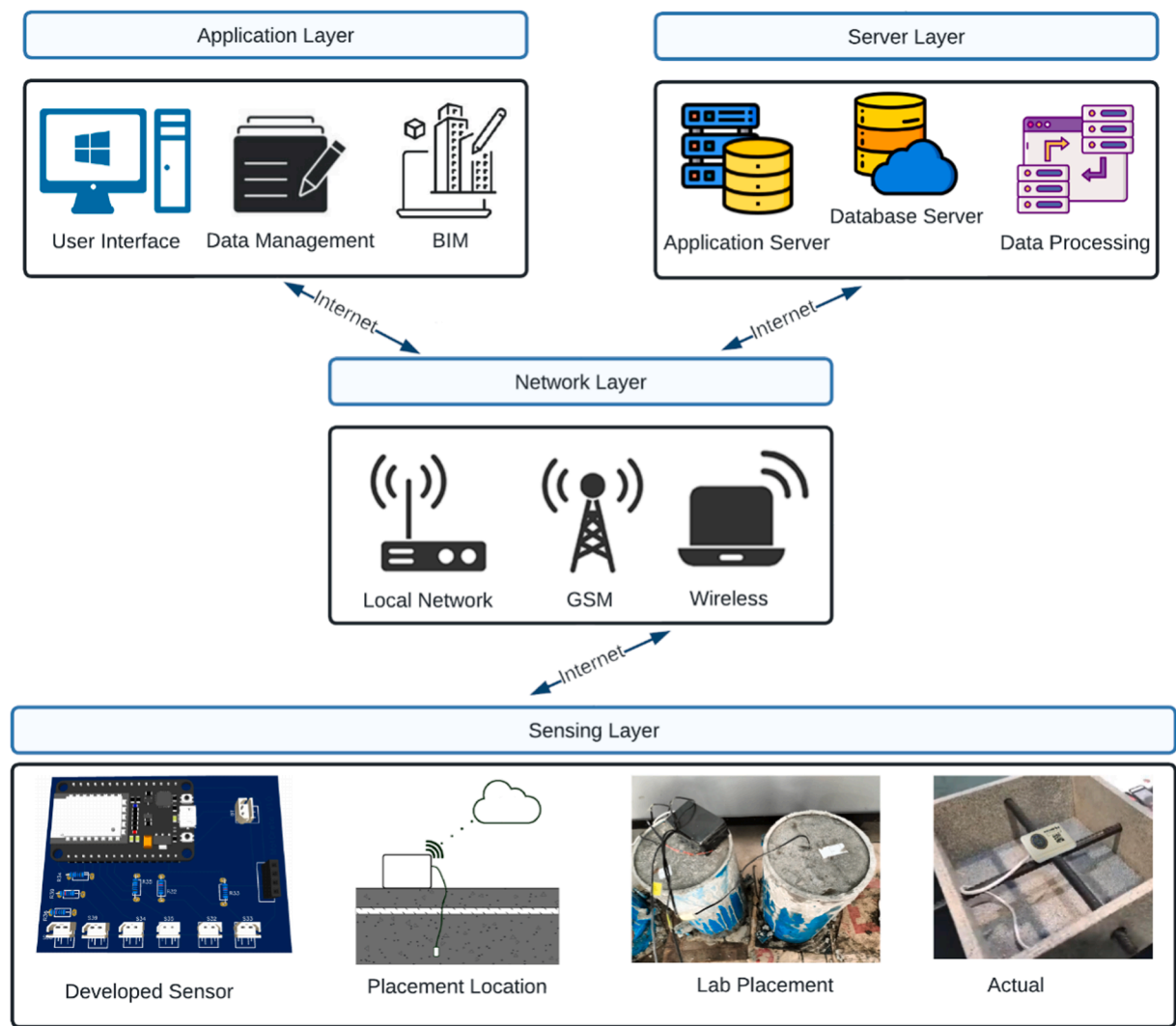


Fig. 3. Architecture of real-time concrete strength monitoring.

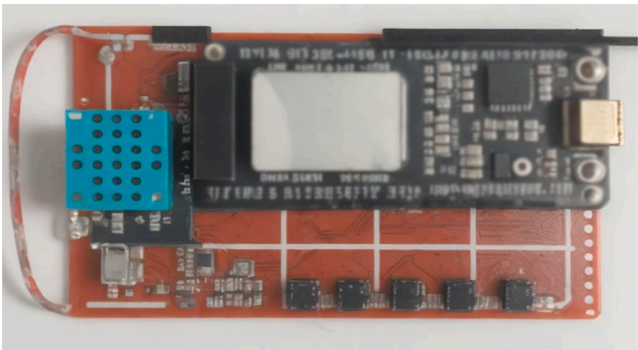


Fig. 4. Depiction of the developed device for recording the maturity of concrete.

developing countries.

The NTC thermistor is encapsulated in a steel sleeve covered with an epoxy rinse. NTC thermistor, short for Negative Temperature Coefficient thermistor, is a type of temperature sensor that exhibits a decrease in resistance as temperature rises. This characteristic allows it to accurately measure and monitor temperature changes in various applications such as temperature control systems, automotive, and electronic devices. Its compact size, sensitivity, and low cost make it widely used in temper-

Table 1		
Description of sensors used in real-time concrete strength monitoring.		
ESP32 Wroom	Operating Voltage	2.2 V ~ 3.6 V
	Current Receiving and Transmitting	80 mA
	Data Rate	54 Mbps
	Flash Memory	4 MB
DHT22	Operating Voltage	3.5 to 5.5 V
	Operating Current	0.3 mA
	Humidity Measuring Range (%)	0 ~ 100 ± 1
	Temperature Measuring Range (°C)	−40 ~ 80 ± 0.5
NTC 10K	Maximum Operating Voltage	5 V
	Maximum Operating Current	0.1 mA
	Resistance at 25 °C	10 k
	B Constant	3380 K ± 1
	Temperature Measurement Range	−20 ~ 105 °C
	Temperature Measurement Precision	±0.05 °C to ± 1.00 °C

ature sensing applications [50]. As the relationship between resistance and temperature is nonlinear, certain approximations must be made when utilizing this relationship. The Steinhart-Hart formula is currently considered the most accurate approximation available for this purpose [51].

$$\frac{1}{T} = A + B \times \ln(R) + C \times (\ln(R))^3 \quad (4)$$

where natural logarithm of the resistance at a given temperature T in Kelvin, represented by $\ln R$. Coefficients A , B , and C , derived from experimental measurements, are used in the formula and can be found in the thermistor vendor's datasheet. The Steinhart-Hart formula, which employs these coefficients, provides an accuracy of roughly $\pm 0.15^\circ\text{C}$ within the range of -50 to $+150^\circ\text{C}$, making it suitable for use in the maturity device.

To gauge temperature, a voltage divider circuit can be employed. This circuit is composed of a known resistor (R_1) that is connected in series with a thermistor (R_t). To measure the temperature, a voltage reference (V_s) is applied to one end of the resistor, while the other end of the thermistor is connected to the ground. The voltage across the thermistor (V_o) is then read, and the temperature is determined based on the voltage reading [52,53]. Since the resistance of the thermistor is temperature-dependent, there will be corresponding variations in the voltage output (V_o). These voltage changes can be conveniently detected using the Analog-to-Digital Converter (ADC) input pins on the ESP32 Board [54].

$$R_t = R_1 \times \frac{4095}{V_o - 1.0} \quad (5)$$

where R_t is the resistance at the temperature T , R_1 is the known resistor used as a voltage divider V_o is the read voltage by esp32. Once the voltage is determined the resistance is calculated from it by using Eq. (4). Which is further utilized in the Steinhart-Hart formula to calculate the required temperature.

4.3.2. Real-time database

Once the temperature is calculated it is transmitted to a real-time database by the esp32 through Wi-Fi over a local network. In this project, the Firebase real-time database has been used. Firebase is a cloud-based development platform. It provides features such as authentication, cloud storage, hosting, and analytics, enabling developers to quickly develop and deploy applications without the need for complex backend infrastructure. Additionally, the system offers a dynamic NoSQL database that enables the real-time storage and retrieval of data [55]. The information is stored in JSON format, and it is accessible through a RESTful API. With Firebase, real-time data syncing between IoT devices and the cloud was set up, which is the ultimate requirement of real-time data management [56]. Moreover, firebase does offer a free tier that has a generous number of resources ideal for developers who are just starting or testing applications.

4.3.3. Monitoring dashboard

In this study, a window-based Monitoring Dashboard for the concrete strength can be seen in Fig. 5. The application was developed in Python language along with various libraries. PyQt was used to design the application's user interface [57]. The study adopted Python due to its open-source nature along with a huge and growing ecosystem of open-source packages and libraries. The connection between the monitoring dashboard and the cloud database was done through the Firebase library. Firebase offers Firebase facilitated remote data access, enabling convenient availability for subsequent analysis. For visualization of data, collected from the concrete Matplotlib was utilized. To develop a regression model for the best-fit curve of strength against maturity the Scikit-learn (sklearn) library was employed, which provides a diverse set of machine-learning algorithms and tools specifically designed for regression and classification tasks.

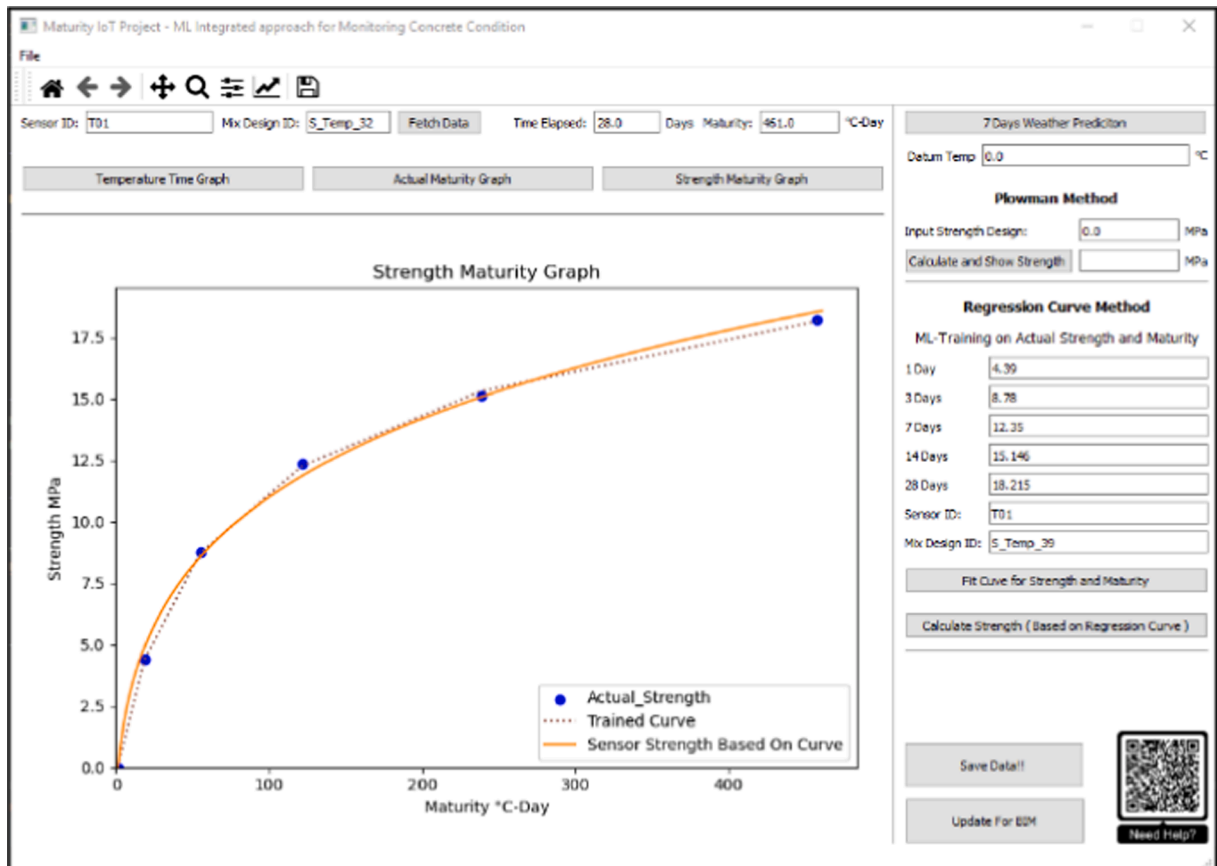


Fig. 5. Developed window monitoring dashboard.

The dashboard developed for IoT-based concrete strength monitoring offers several user-friendly features to access and analyze sensor data effortlessly. It provides real-time temperature data, keeping users informed about the current maturity of the concrete. With a single click, users can calculate the real-time strength of the concrete, employing different strength calculation methods: Plowman's method and the Regression Curve method. Fig. 6 illustrates the data flow chart for the monitoring dashboard. Once the data has been transmitted to the cloud, with the help of the window application the temperature data is retrieved back by inputting the sensor ID and mix design ID. These parameters are usually kept the same unless one sensor is used to monitor two different parts having different mix designs. Once the data has been loaded into the application the user can preview the temperature–time graph of the concrete which will indicate if the sensor is functional or not and how long the data has been recorded. After that, the user can calculate the maturity of the concrete from the temperature time graph which gives the user the option to either use the plowman's method or use the previously recorded maturity curve developed in a controlled environment. When the user opts for the Plowman method, he would be required to input the datum temperature and design strength so that the dashboard can load the parameters of a & b used in the Plowman equation after which strength will be calculated and displayed. If the user opts to use the pre-developed maturity curve he would be required to input the sensor ID and mix ID of the prerecorded temperature data which is saved in the database and then he would input the strength 1,3,7,14,28 days. From this data, the application will develop a maturity-to-strength curve which will be used as a reference for maturity calculated on-site so that the strength can be calculated. Additionally,

the application provides a 7-day temperature forecast obtained from the weather bit forecast server to better predict the ambient temperature on a construction site [58].

4.3.4. Method of using RTCSM

To use the real-time concrete strength monitoring the datum temperature is first to be determined for the mix design. According to ASTM C1074, For Type I cement, a datum temperature of 0 °C is recommended, assuming that the mix does not contain any admixture and the curing temperature ranges between 0 to 40 °C. In the early studies, the datum temperature for the maturity method was defined as −10 °C [59], but research has indicated that the datum temperature for a specific cement type can range between 0 and −10 °C. Adopting a 0 °C datum temperature is often considered conservative because it assumes no strength gained if the concrete temperature drops below freezing point. The procedure to determine the datum temperature has been provided in detail in ASTM C1074 [60]. Once the datum temperature has been determined the maturity of the concrete is then calculated and converted into strength by any of the two methods available in the developed window-based monitoring dashboard. The main process included in concrete strength determination is summarized as follows:

The IoT device and the Firebase database are set by changing the Wi-Fi credentials on the IoT device so that it can connect to a local network and a unique sensor ID and mix ID is assigned, to set up the Firebase database, an account is needed to create a real-time database. The API key is obtained from the settings page of the real-time database [61,62].

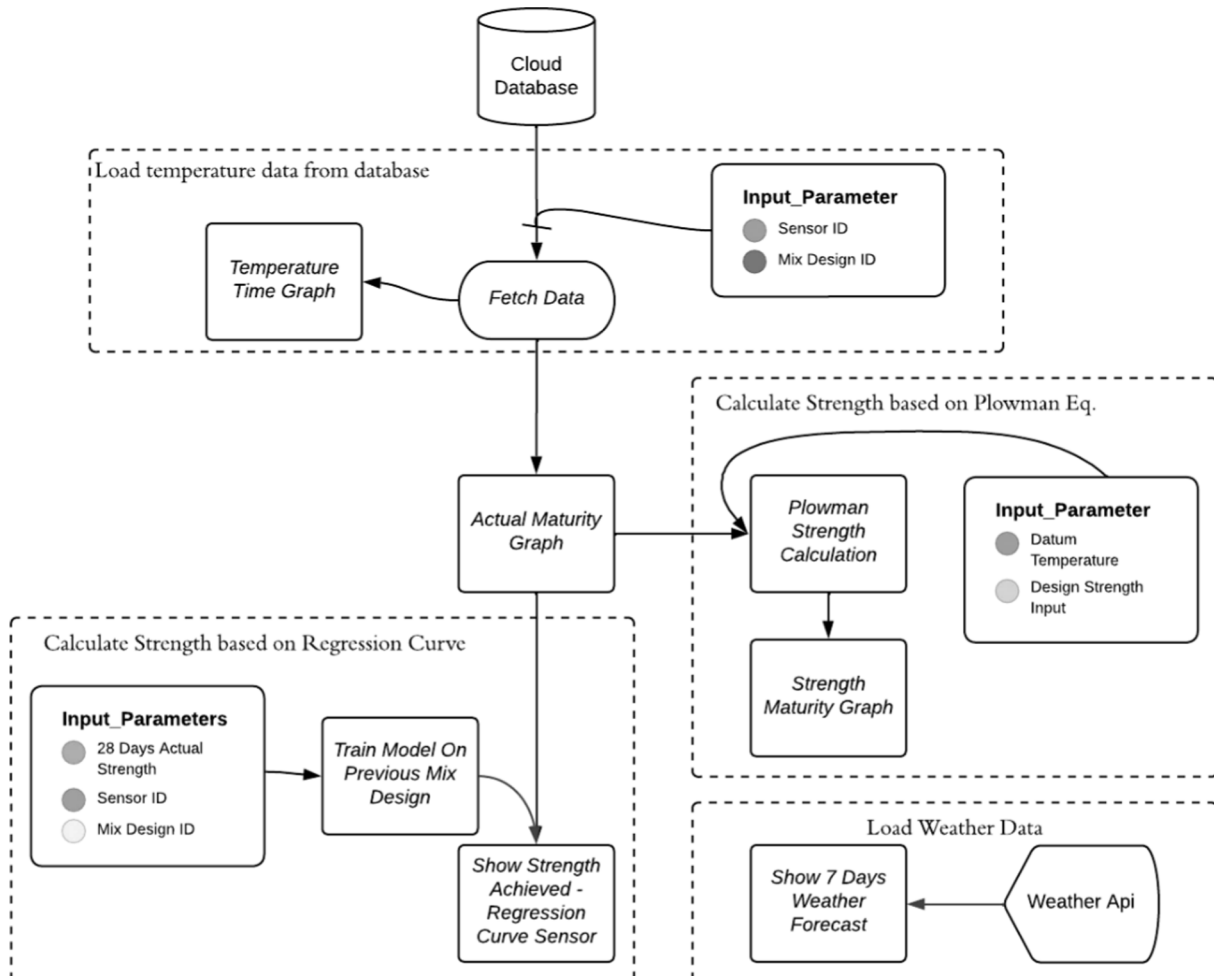


Fig. 6. Data flow chart for window monitoring dashboard.

The internal temperature of the concrete is monitored by embedding the temperature sensor module within ± 15 mm inside the concrete. The critical placement location for the sensor in the building component can be seen in Fig. 7. The placement location of the sensors depends on the pour schedule, structurally critical locations, and colder locations. Upon placement, the device starts storing the concrete core temperature and ambient temperature as well as humidity data on the cloud. The frequency of data collection by the IoT device is 30 min as required by the standards.

To remotely monitor the concrete compressive strength. A unique API key from the cloud database is assigned to each user which is then entered into the developed monitoring dashboard. The temperature data of the sensor is retrieved from the database by entering the sensor ID. The real-time maturity of the concrete is calculated after entering the datum temperature. To calculate the strength, for the Plowman method the variables a and b are determined by the window application from the entered mix design strength. However, for the regression method concrete strength at 1, 3, 7, 14, and 28 days strength as well as the temperature time history is entered in the left menu of the monitoring dashboard. The temperature history for specific mix designs can be loaded to the dashboard by entering the mix design ID along with the sensor ID. The window application based on the regression model will determine the best-fit curve for the strength and maturity then it calculates the strength. The data including the temperature history of the sensor can be saved in an *xlsx* file or it can be stored and transmitted to BIM tools from the lower right corner of the monitoring dashboard.

5. Experimental design (case study)

To evaluate the feasibility and effectiveness of an integrated IoT and BIM system for monitoring concrete strength during early construction stages, a case study was conducted at the site of the new Girls Hostel, a multi-story building, at GIK Institute. During this phase, the focus was primarily on monitoring the structural elements, including columns and beams as they were being constructed. The study was mainly done on the elements of ground level. The study site was chosen based on easy access, the availability of power, and local internet access, ensuring seamless integration and operation of the monitoring system. Additionally, access to the BIM model and construction schedule facilitated the alignment of monitoring activities with the ongoing construction progress.

5.1. Test materials and pre-calibration

Two concrete mixtures, Mix 1 and Mix 2, were used to assess the

performance of the proposed system by determining the concrete's early-age compressive strength using the created framework. Grade 53 Type 1 cement was used in the mix design and the datum temperature was kept at 0. The mix design was prepared based on ACI mix design guidelines can be seen in Table 2 [63]. A total of 10 cylinders were cast for each mix design based on ASTM C 31 standards as can be seen in Fig. 8a. The thermistor sensors were embedded in the concrete specimens as shown in Fig. 8b. The internal temperature-time history data of the concrete was recorded by the developed device at an interval of 30 min then the data was transmitted to the cloud database via the wireless network. Using the uniaxial compression machine, the 1, 3, 7, 14, and 28 days strength was determined. The temperature data recorded by the device and equivalent age can be seen in Fig. 8c and d. The compressive strength of the mix design and Strength-age relationships for the concrete mixes were established based on the regression curve in the monitoring dashboard as can be seen in Fig. 8e.

5.2. Field implementation

The strength maturity relation obtained from the pre-calibration process was then utilized in the in-situ testing of the concrete strength of the column. Mix 2 was being used on the site for the construction of columns. The developed sensor was placed in the lower bottom of the column as shown in Fig. 9.

Since the construction site doesn't have any wireless connection nearby a GSM-based internet device was placed near the device. The device recorded the temperature of the concrete in the column and stored it on the real-time cloud database. The monitoring dashboard retrieved the database from the database and calculated the maturity of the concrete in the column element. The maturity of the concrete was converted into strength using both the Plowman method and the regression model developed in the earlier section for the Mix 2 mix design. The results from the Plowman method and the regression can be

Table 2
Concrete Mix Design Description.

Parameter	Mix 1	Mix 2
Design Strength MPa	8	20
Cement Type	OPC Type 1	OPC Type 1
Density (kg/m ³)	2335	2365
W/C	0.79	0.48
CA (kg/m ³)	971	956
FA (kg/m ³)	1062	906
W (kg/m ³)	240	242
Cement (kg/m ³)	303	503

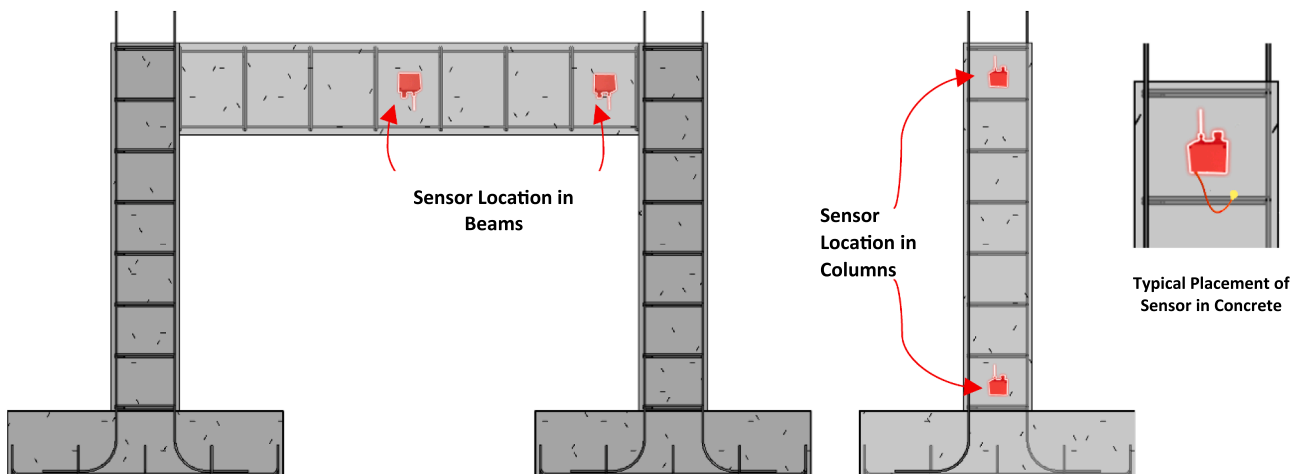


Fig. 7. Critical placement location for thermistor probe in RC frame and vertical members.

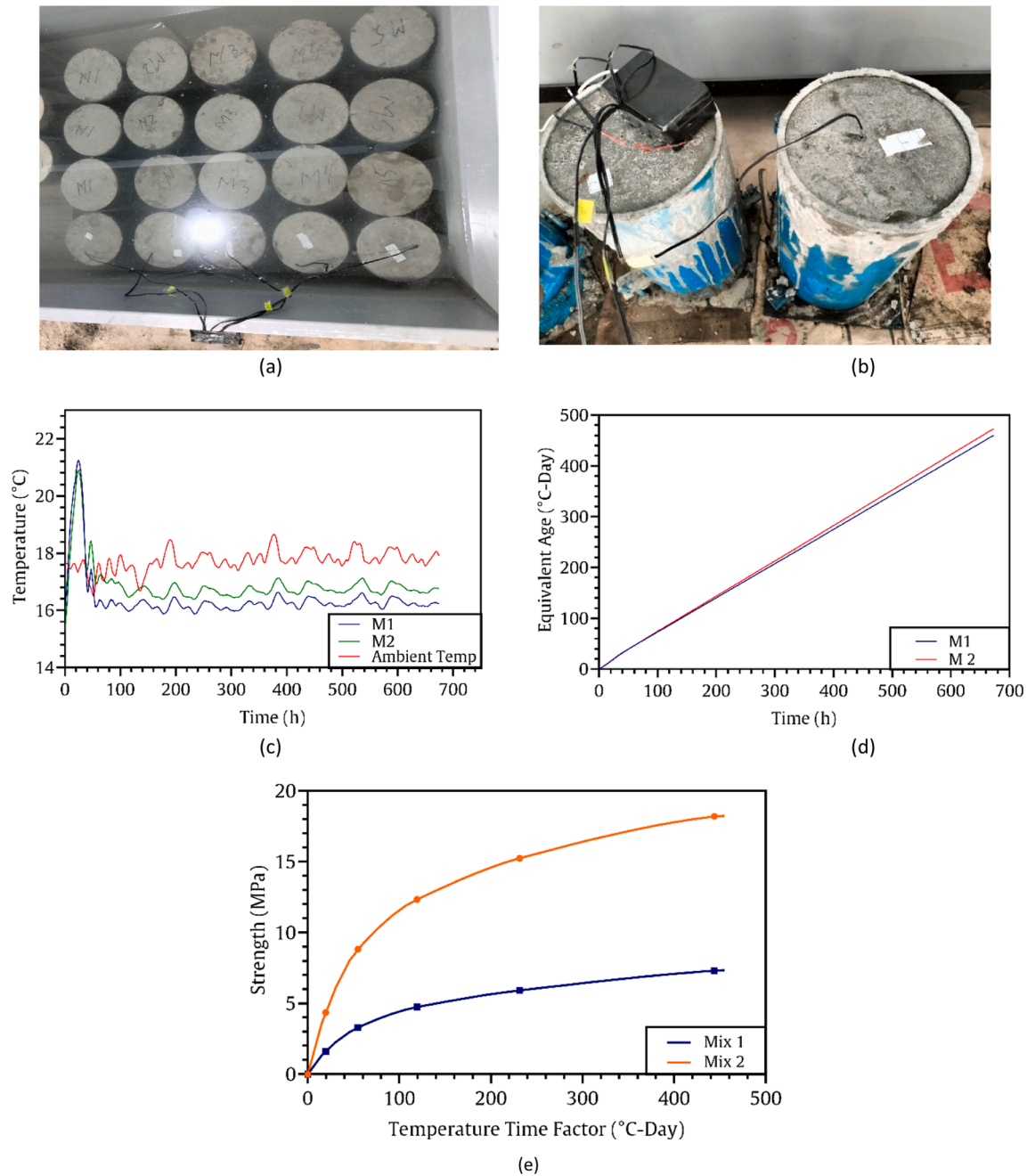


Fig. 8. Experimental setup (a) concrete cylinder casted for each mix design (b) sensor location in the concrete specimen (c) Temperature history of the mix design (d) Equivalent age of the mix design (e) compressive strength of the mix design and Strength–age relationships.

seen in Fig. 10a.

Apart from determining the strength using RTCSM concrete cylinders were also casted on-site to compare the accuracy of the system with uniaxial compression machine results. As from Fig. 12b, it can be seen that there is a negligible difference in the strength throughout the month. But since this is an approximate method to calculate the strength negligible difference is admissible. The strength determined in the monitoring dashboard is then synced to the BIM tool for visualizations to create a DT.

6. BIM integration

Incorporating the IoT sensor data and Revit model to develop a DT is the concluding phase of this research. To accomplish this, the functionalities offered by Autodesk Navisworks are utilized. The data loaded

from the database is exported to a local Excel file using the developed window application the Excel file is then linked with the Navisworks model to synchronize the data from the database to the model. The overall flow is illustrated in Fig. 11.

Navisworks stands out as a prominent BIM viewer application, valued for its user-friendly interface and robust capabilities in construction planning. Its seamless integration with Revit for importing 3D models and performing tasks like 4D time-lining and clash detection underscores its versatility. The study's choice of Navisworks as a BIM tool was motivated by the availability of custom plugins developed by numerous authors, facilitating the integration of specialized data into the BIM model. Synchronization options range from custom plugin development to utilizing APIs or leveraging built-in data tools, enabling connectivity with various databases. This flexibility in synchronization methods underscores Navisworks' adaptability to diverse project needs



Fig. 9. Sensor placement in the field.

and data sources. Furthermore, Navisworks has a free educational license which allows the institute to use the product for free. Furthermore, Navisworks also can deal with construction schedules thus making it an

excellent choice if the optimization of the schedule is to be carried out.

Autodesk Revit and Navisworks 2018 software was selected as the BIM platform. Navisworks is extensively utilized for tasks such as visualization, database connectivity, simulation, and appearance profiling. To execute this approach, three preliminary steps were carried out using the Revit software [64]. First, a structure model of the case study was made in Revit as can be seen in Fig. 12a. After two new shared parameters, namely Sensor ID and Strength were created for the structural element where the sensor was placed. Then these parameters were loaded into the Revit model and connected with the elements; in our case, it is the column. Finally, the Revit model was exported to Navisworks through the export as an NWC file. NWC is a native file type for Navisworks which is then converted to a NWD file.

In this study, the DataTools functionality of Autodesk Navisworks software is used to establish and oversee connections between the Navisworks model and the database. Navisworks' DataTools allow users to efficiently manage and integrate external data into the model. This functionality facilitates seamless connectivity with diverse data sources, enabling users to import, manipulate, and analyze information alongside their project models. Whether it's importing data from spreadsheets, databases, or other applications, DataTools streamlines the process by synchronizing project data with their Navisworks models, enabling a comprehensive understanding of project parameters and facilitating optimization operations for construction schedules. The DataTools option is located under the Home Tab of Navisworks. In this study, the connection between the Navisworks and Database is established through a local Excel file which is connected to a Firebase database through a custom-built window application. This process is a well-recommended method for adding external bulk data [65]. The "DataTools" function utilized an Open Database Connectivity (ODBC) driver to establish a connection with the locally generated Excel file. Standard

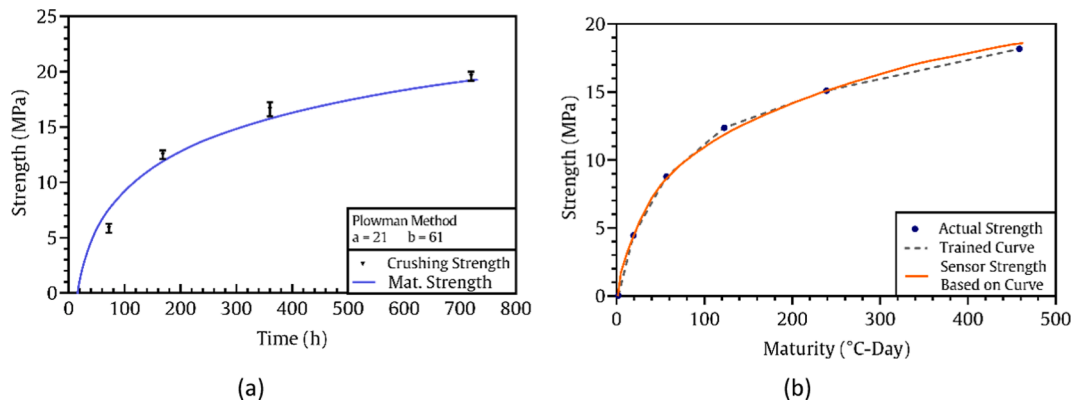


Fig. 10. In-situ concrete strength is determined via (a) Plowman methods and (b) regression curve.

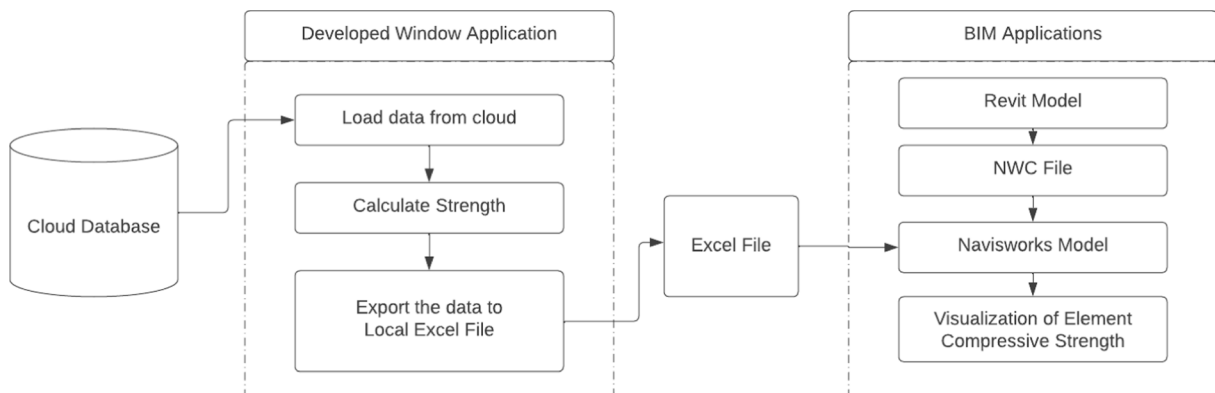


Fig. 11. Data integration flowchart for Navisworks.

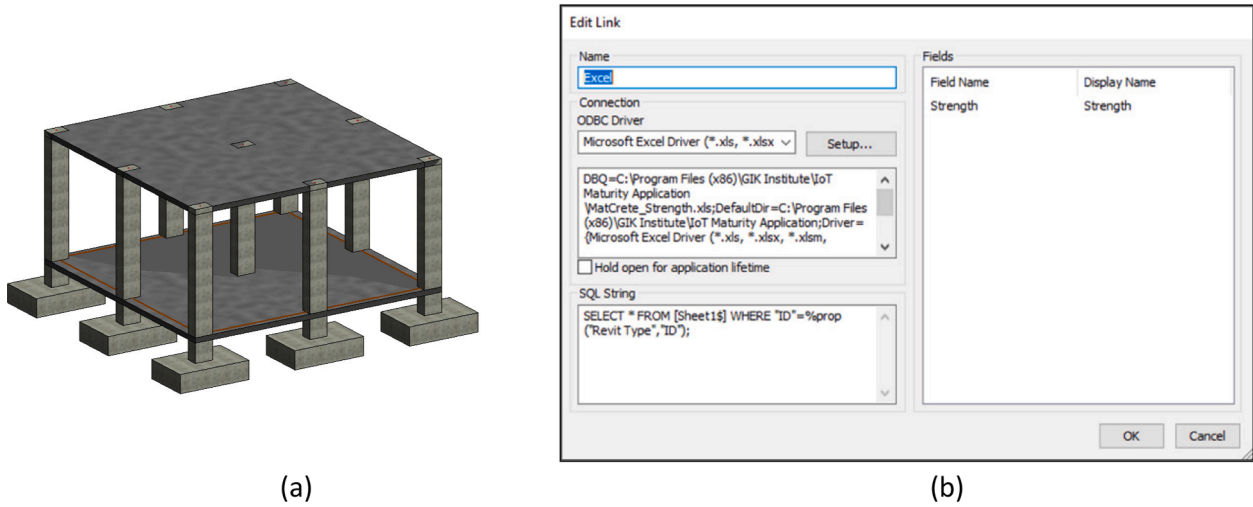


Fig. 12. (a) 3D model frame structure in Revit (b) ODBC link with Excel file and SQL String for data connection.

query language (SQL) string loads the data from the Excel file into the Navisworks [66]. An instance of the query with the SQL statement is demonstrated in Fig. 12b as an example.

Once the data has been loaded to the BIM model from the local Excel file created through the developed window application. To visualize the data stored on the database “Appearance Profiler” feature of Navisworks was used. Custom appearance profiles and color-code objects based on their strength values were defined. The study specifically used three distinct color codes for columns. When the strength of the element was less than 5 MPa the element was supposed to appear red. When the strength of the element is in the range between 5 to 10 MPa the element color is supposed to be yellow and when the strength gets more than 10 MPa the elements are supposed to appear green. The visualization of concrete compressive strength in the BIM model through appearance

profiles is an application that utilizes the concrete compressive strength parameters recorded in real-time through IoT devices. The visual appearance is to indicate when sufficient strength is attained by the concrete and the schedule can be progressed. These strength parameters, utilized by the appearance profile, can also be connected to the construction schedule to automatically complete the activities dependent on concrete strength. The color rule adopted in this study for performance testing purposes is illustrated in Fig. 13.

This synchronization process, facilitated by Navisworks’ DataTools feature, allows for the establishment of real-time connections between the digital representation of the project and its physical counterpart. By collecting the compressive strength of element structures sensors and visualizing sensor data alongside the Revit model, Navisworks transforms into a DT, providing stakeholders with a comprehensive and

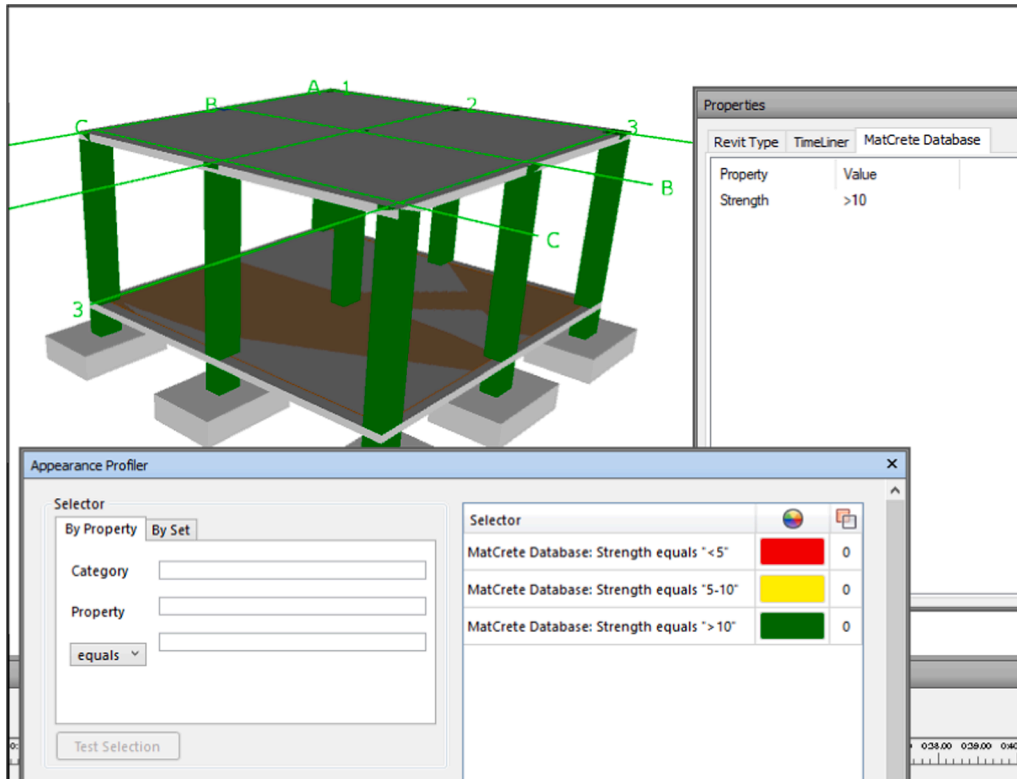


Fig. 13. The color rule for monitoring the strength of concrete.

nearly real-time understanding of the construction site. This integration of Revit models and sensor data enables nearly real-time 3D visualization of concrete compressive strength. This visualization not only serves as an indication of concrete elements casted on site but also provides insights into the compressive strength of elements in a digital environment. This approach allows construction and project managers to quickly identify areas that are lagging behind from baseline schedule as well as allows them to take instantaneous actions like the removal of formwork, post tensing, termination of curing, and removal of reshores [67]. This approach offers several advantages as it eliminates any constraints associated with the size of the model, allowing for the visualization of intricate single structures or clusters of buildings. Furthermore, the BIM platform can visualize models generated by various other BIM software providers as well through the International Foundation Class (IFC) [68], including ArchiCAD and Rhino. By incorporating Revit models and sensor data into Autodesk Navisworks Manage, an innovative method emerges to remotely monitor the real-time compressive strength of concrete and visualize it in a digital replica for early identification of issues, benefiting project managers. While this study was carried out with Autodesk Products it does not limit the use of the framework to these products the framework can be adopted in other platforms, software, or tools developed based on the openBIM system.

7. Discussion

To ensure effective construction scheduling, it is critical to monitor the compressive strength of concrete in real time, particularly during the early stages. The early age strength of concrete is often necessary for various activities, such as formwork removal, opening traffic on concrete pavements, post-tensioning, concrete curing, and applying loads to concrete elements during construction. Little literature is available regarding the determination of early-age concrete compressive strength [69]. According to existing literature, the determination of early age strength can be achieved through two methods: (1) effective control over the proportions of materials used in the concrete mixture, and (2) manipulating the curing temperature to accelerate cement hydration [70]. This study introduces an IoT-based system to monitor the concrete strength in real-time and integrate the outcome with BIM through wireless sensors and IoT framework creating a DT. Traditionally concrete strength monitoring technique requires skilled personnel to cast cylinders as per standards and then transport them to the laboratory for crushing. By utilizing this method, the need for skilled construction workers may be reduced, which is the need for time. Unlike previous research that focused on BIM-assisted design and planning of worker safety, 3D modeling, concrete structure, and formwork settings [71], this study emphasizes the monitoring aspect, which has implications for construction management and project controls. To validate the effectiveness of the system, a case study was conducted on an actual construction project, which revealed significant time reductions in formwork removal compared to the standard recommendations.

One key implication of this study is that sensor data can be seamlessly transmitted to the BIM environment via a window application that retrieves the data over the internet from the Firebase cloud database allowing for real-time monitoring of concrete status. The research presented here introduces a sensor module and window application that enhances the interoperability of BIM by enabling real-time monitoring of concrete strength and control of construction activities.

Another important finding is that the developed BIM-based system enables the project manager to schedule early formwork removal for different structural elements on site. The utilization of concrete formwork systems is of utmost importance in constructing reinforced concrete structures. Specifically, the expenses associated with formwork construction and the time required for formwork erection and assembly significantly impact both the overall cost and duration of the construction project. These factors can account for approximately 10% and 50% of the total project cost and construction timeline [72]. The suggested

system enables professionals to consistently observe and regulate the process of concrete placement, thereby enhancing the scheduling of activities involved. By deviating from the manual standards and removing formwork earlier while ensuring strength, project delays and unnecessary expenses related to formwork rental can be avoided. This results in a reduction of both time and cost, benefiting the overall process of concrete formwork and facilitating timely project completion.

This study mainly integrates IoT-based devices with BIM for concrete strength monitoring. For future advancements, this study recommends studies to develop a framework that integrates IoT-based devices with an open-source BIM modeling engine. The recent development of open-source libraries and IFC-based BIM engines has made it easy to develop customized BIM software and web platforms. The customized IFC BIM platform can also be integrated with the construction schedule as reported by multiple authors [73]. Once a project schedule has been linked to the customized BIM engine. The platforms can then be made a centralized monitoring platform by connecting different IoT-based devices for tracking like imaging equipment, bar codes, RFID tags, and even laser scanners to form a DT. This DT with the ability to track the core activation of the construction schedule can also be used to optimize the schedule based on Active BIM approaches to avoid delays and cost overrun [74]. The study further suggests a detailed cost-benefit analysis of IoTs use in tracking construction activities and a detailed study to quantify the effect of the BIM-integrated IoT-based maturity devices on project schedules and cost on construction projects of different natures.

7.1. Limitation

The proposed framework for concrete strength monitoring offers several advantages over the traditional process by enabling remote monitoring and nearly real-time data processing. It provides a more accurate representation of in-place concrete strength gain and allows for in-place strength measurements at any time and as frequently as needed until the desired strength is achieved. These features enhance the construction process by facilitating better timing for strength-dependent activities, leading to cost savings and improved efficiency.

However, the framework does have inherent limitations that need to be addressed. One of the main limitations is that it does not account for the effects of early-age concrete temperature on the long-term ultimate strength. For normal-strength Portland cement concrete, higher early-age curing temperatures can result in lower strength at later ages compared to initial lower early-age curing temperatures. This limitation should be taken into consideration while interpreting the strength data obtained through the maturity method.

Moreover, the maturity method should be supplemented by other indicators to verify the potential strength of the concrete mixture. ASTM C 1074 requires verification of the in-place concrete's potential strength before critical operations, such as formwork removal or post-tensioning, to ensure that the correct mixture proportions are in place. While the IoT-based device continuously stores data on a cloud database in real time, there are still some manual steps involved in the data retrieval process. Loading the data on the window monitoring dashboard and then importing the results to Navisworks requires human intervention, which could introduce some delays and potential errors in data handling.

In the digital twin section, the study just connects the data with the BIM model to be visualized by the project manager. To optimize the framework further, efforts could be made to link the data further to the construction schedule of the project to optimize the construction schedule with no human interaction. Furthermore, one of the potential challenges in the adoption of the BIM-IoT framework is the limitations in data transfer capacity and data security [75]. This study uses encryption and authentication to enhance data protection and the Google Firebase-based database, however for further improvement blockchain technologies could be adopted for data protection.

8. Conclusion

Early-age concrete compressive strength monitoring is a crucial activity for effective construction scheduling. Traditional methods of concrete strength evaluation, such as periodic testing and manual data collection, no longer meet the demands of the modern construction industry. IoT technology and BIM tools have emerged as a viable and promising solution to tackle these difficulties. By utilizing IoT sensors embedded within concrete structures, real-time data on concrete compressive strength can be collected and analyzed remotely. This data, integrated with BIM, allows stakeholders to visualize and analyze the concrete strength parameters in a virtual environment providing valuable insights into the performance of concrete structures and enabling informed decision-making throughout the construction process. The proposed system offers the benefits of remote monitoring, early identification of potential issues, and Active BIM approaches to optimized construction workflows to improve efficiency, quality control, and proactive risk management within construction projects.

Credit authorship contribution statement

Fahad Iqbal: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Shiraz Ahmed:** Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – original draft. **Muhammad Abu Bakar Tariq:** Formal analysis, Methodology, Software, Supervision, Validation, Writing – original draft. **Hafiz Ahmed Waqas:** Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Essam A. Al-Ammar:** Funding acquisition, Project administration, Validation, Visualization, Writing – review & editing. **Saikh Mohammad Wabaidur:** Funding acquisition, Project administration, Resources, Validation, Writing – review & editing. **Muhammad Fawad:** Funding acquisition, Project administration, Resources, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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